DEFENSE NUCLEAR FACILITIES SAFETY BOARD

Washington, DC 20004-2901

July 6, 2017

Mr. James M. Owendoff
Acting Assistant Secretary for
Environmental Management
U.S. Department of Energy
1000 Independence Avenue, SW
Washington, DC 20585-1000

Dear Mr. Owendoff:

In a letter dated August 21, 2015, the Defense Nuclear Facilities Safety Board (Board) expressed concern with the removal of a specific administrative control (SAC) in the Hanford Sludge Treatment Project (STP) Engineered Container Retrieval and Transfer System (ECRTS) preliminary documented safety analysis (PDSA). By letter dated November 18, 2015, Dr. Monica Regalbuto, Assistant Secretary for Environmental Management, asserted that the ECRTS PDSA demonstrates adequate protection of the public and the SAC is unnecessary.

Based on our analysis, we concur that the control set documented in Revision 2 of the ECRTS PDSA provides adequate protection to the public on the Columbia River. The enclosed Technical Report, DNFSB/TECH-41, contains our independent analysis of spray release accidents at STP and is provided for your information and use as you deem necessary.

Sincerely,

Sean Sullivan
Chairman

Enclosure

c: Mr. Joe Olencz

DNFSB/TECH-41

SPRAY RELEASE ACCIDENTS AT THE HANFORD SLUDGE TREATMENT PROJECT

Defense Nuclear Facilities Safety Board

Technical Report

June 2017

DNFSB/TECH-41

SPRAY RELEASE ACCIDENTS AT THE HANFORD SLUDGE TREATMENT PROJECT

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EXECUTIVE SUMMARY

In an August 21, 2015, letter the Defense Nuclear Facilities Safety Board (Board) expressed concern with the Department of Energy's (DOE) removal of a specific administrative control (SAC) from the Sludge Treatment Project (STP) Engineered Container Retrieval and Transfer System (ECRTS) preliminary documented safety analysis (PDSA). The SAC was originally included in the ECRTS PDSA to control public access to the Columbia River prior to and during slurry transfers of radioactive material. The Board's letter thus requested a report from DOE describing DOE's position on, and technical basis for, controlling Columbia River access and protecting members of the public from spray release accidents during slurry transfers. The DOE report concluded that the control strategy as defined in ECRTS PDSA Revision 1 was adequate to protect members of the public on the Columbia River and that the SAC was no longer needed.

The Board's staff performed an independent analysis of the STP spray release accident and found that the "fog model" approach used in the STP ECRTS PDSA may be adequate if the K Basin sludge forms spherical agglomerate droplets in the spray. If the K Basin sludge tends to form fractal-shaped agglomerate droplets during evaporation, the STP methodology does not bound experimental correlations. It is important to note that the staff team's methodology assumes that the dried agglomerates do not break up into smaller particles during transport to the receptor. Consideration of agglomerate break-up due to shear forces for droplets larger than respirable size could lead to a larger population of respirable droplets and a greater dose consequence. The staff team's methodology predicts unmitigated dose consequences greater than 5 rem total effective dose (TED) but less than 25 rem TED. According to DOE Standard 1189-2008, *Integration of Safety into the Design Process*, this range challenges the Evaluation Guideline defined in DOE Standard 3009-94, *Preparation Guide for U.S. Department of Energy Nonreactor Nuclear Facility Documented Safety Analyses*. DOE Standard 1189-2008 states that "SC [safety class] designation should be considered, and the rationale for the decision to classify an SSC [structure, system, or component] as SC or not should be explained and justified." However, based on the staff team's assessment, the staff team believes that the current control strategy of STP is adequate in protecting the public and the workers from radiological dose consequences associated with a K Basin sludge spray release event.

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1. INTRODUCTION

Members of the Defense Nuclear Facilities Safety Board's (Board) staff reviewed Revision 1 of the preliminary documented safety analysis (PDSA) for the Engineered Container Retrieval and Transfer System (ECRTS) phase of the Sludge Treatment Project (STP). The staff's review identified concerns with the project team's removal of a specific administrative control (SAC) from the PDSA that was used to limit access to the Columbia River to protect the public during slurry transfers.

The Board transmitted a letter and staff issue report to the Department of Energy (DOE) on August 21, 2015, requesting: 1) DOE's position on controlling Columbia River access and protecting members of the public from accidents during slurry transfers, and 2) the technical basis for DOE's position. DOE's November 18, 2015, response provided the information requested by the Board. DOE concluded that the public is adequately protected, citing: 1) the reduced unmitigated dose consequence to members of the public on the near bank of the Columbia River due to changes to the inputs and assumptions used in the spray release analysis, 2) the short transfer time of engineered container SCS-CON-230, and 3) the safety significant shutoff switch that terminates power to the booster pump during a seismic event.

The Board's staff performed an independent analysis of the STP spray release accident and found that the "fog model" approach used in the STP ECRTS PDSA may be adequate if the K Basin sludge forms spherical agglomerate droplets in the spray. If the K Basin sludge tends to form fractal-shaped agglomerate droplets during evaporation, the STP methodology does not bound experimental correlations. The staff team's methodology predicts unmitigated dose consequences greater than 5 rem total effective dose (TED) but less than 25 rem TED. According to DOE Standard 1189-2008, *Integration of Safety into the Design Process* [1], this range challenges the Evaluation Guideline defined in DOE Standard 3009-94, *Preparation Guide for U.S. Department of Energy Nonreactor Nuclear Facility Documented Safety Analyses* [2]. DOE Standard 1189-2008 states that "SC [safety class] designation should be considered, and the rationale for the decision to classify an SSC [structure, system, or component] as SC or not should be explained and justified." However, based on the staff team's assessment, the staff team believes that the current control strategy at STP is adequate to protect the public and workers from radiological dose consequences associated with a K Basin sludge spray release event.

2. BACKGROUND

The STP is a subproject of the K Basins Closure Project at the Hanford Site. The mission of the STP is to dispose of the radioactive sludge currently stored at the 105 K West Basin. The sludge is a combination of metallic spent fuel corrosion products (i.e., particulates of uranium oxides and uranium metal), debris from fuel storage racks and containers, windblown dust, and spallation products from the fuel basin concrete walls and floors. Appendix D lists the radionuclides of concern contained in the Engineered Container SCS-CON-230 sludge. The sludge is stored underwater in six engineered containers within the K West Basin.

Phase I of the STP, referred to as ECRTS, will transfer approximately 27 cubic meters of sludge in multiple batches as slurry through a hose-in-hose transfer system into the sludge transport and storage containers (STSCs) located in the sludge loading bay of the K West Basin Annex. The K West Basin Annex is located approximately 12 meters north of the K West Basin and approximately 520 meters from the near bank of the Columbia River. Once loaded, trucks will transport the STSCs in sludge transport system casks to T-Plant for interim storage before the sludge is treated and sent to the Waste Isolation Pilot Plant. Transferring the sludge from the K West Basin initially increases risk to the public by introducing a new hazard during operations of ECRTS. However, the end state overall risk to the public is reduced by moving a significant hazardous source term away from the Columbia River. Removing the sludge also allows DOE to access and treat a hazardous chemical plume underneath the K West Basin.

Spray releases are one of the major accidents by consequence identified in the ECRTS PDSA. Spray release accidents can be initiated by operational events, a facility fire, natural phenomena hazards, or external events. To determine the dose consequence associated with a spray release, the project team uses a correlation-independent approach referred to as the "fog model." DOE has adjusted the approach as the safety basis documents have matured from 2012 to 2015 [3, 4, 5, 6].

In a May 2, 2014, letter, the Board closed all of its open nuclear safety issues related to the STP ECRTS following the staff review of Revision 0 of the ECRTS PDSA [7]. In the enclosure to the letter, the Board concluded that the spray release accident analysis in Revision 0 of the PDSA was technically justified as bounding. The Board noted, however, that the project team was undertaking several nuclear safety initiatives that would likely result in changes to the ECRTS safety basis. One such initiative was revising the spray release methodology to reduce the assumed aerosol concentration of the transferred slurry at 100 meters from the previously assumed value of 100 mg/m^3, which was recommended in American National Standards Institute Standard N46.1-1980: *Guidance for Defining Safety-Related Features of Nuclear Fuel Cycle Facilities* [8], to 12.5 mg/m^3 without a specific technical basis for the exact factor of 8 reduction.

Reducing the assumed aerosol concentration reduced the unmitigated dose consequence due to an operational spray release at the near bank of the Columbia River[1] from 46 rem TED in Revision 0 of the ECRTS PDSA to 2.5 rem TED in Revisions 1 and 2. The unmitigated dose consequence due to a seismically induced spray release is 5.8 rem TED in Revisions 1 and 2. Consequently, the project team removed a SAC from the control strategy used to mitigate the dose consequence to members of the public on the Columbia River due to a spray release accident. The SAC required CH2MHILL Plateau Remediation Company (CHPRC) to notify DOE's Richland Operations Office (DOE-RL) personnel of planned slurry transfers. DOE-RL could then choose to implement measures to control portions of the Columbia River.

In an August 21, 2015, letter, the Board expressed concern with removal of the SAC due to the rapid developing nature of spray release accidents. The Board requested a report from DOE describing DOE's position on, and technical basis for, controlling Columbia River access and protecting members of the public from spray release accidents during slurry transfers.

On November 18, 2015, DOE responded to the Board's letter, concluding that the STP ECRTS PDSA demonstrates adequate protection of the public and that the Columbia River access SAC is not needed [9]. DOE based its conclusions on the following:

- The revised spray leak analysis in Revisions 1 and 2 of the STP ECRTS PDSA reduced the unmitigated dose consequence to members of the public on the near bank of the Columbia River from 46 rem TED to 5.8 rem TED for a seismic spray release and 2.5 rem TED for an operational spray release.

- A safety significant seismic design criteria (SDC)-2 seismic cutoff switch is credited with mitigating the dose consequence due to a seismic spray release by terminating power to the booster pump before a seismic event reaches SDC-2 levels.

- The total retrieval time for SCS-CON-230 sludge is approximately two hours over the one and one-half year project lifetime. A general service timer limits batch sludge transfers to approximately 13 minutes.

Based on the accident analysis and above factors, DOE believes that the public on the Columbia River is adequately protected and that closing public access to the river during sludge transfers is redundant and unnecessary. The Board's staff team, having performed an independent analysis of the STP spray release accident, now agrees with this conclusion.

[1] The STP ECRTS PDSA does not consider the Columbia River to be the location of the maximally exposed offsite individual for comparison of dose consequences to the DOE Standard 3009-94 Evaluation Guideline. Per the Hanford Safety Analysis and Risk Assessment Handbook (SARAH), a receptor on the near bank of the Columbia River is classified as "onsite public," and dose consequences are reported for informational purposes only [35].

3. SPRAY RELEASE ACCIDENT MODELING

The bounding spray release scenario is based on an undetected breach of primary containment that occurs while slurry is being transferred from engineered container SCS-CON-230 in the K West Basin to an STSC in the sludge loading bay located in the K West Basin Annex. The amount of slurry that is released and aerosolized depends on the size of the breach, the discharge pressure of the fluid, the material properties of the fluid, the duration of the release, and the initiating event. To avoid the complexities and uncertainties associated with modeling a spray release, the STP assumes a maximum slurry aerosol concentration resulting in a correlation-independent approach (referred to as the “fog model”) to calculate the dose consequence to a receptor (i.e., a potentially affected member of the public).

3.1. SLUDGE TREATMENT PROJECT MODELING APPROACH

The STP approach assumes a fixed value for the aerosol concentration of the released slurry at 100 meters downwind from the release point. The following relationship is used to determine the respirable, airborne source term:

$$S = \frac{C_{100m} \times t_{tx}}{\rho_{slurry} \times \left(\frac{\chi}{Q'}\right)_{onsite,1189}} \qquad (1)$$

where C_{100m} is the respirable aerosol concentration at 100 meters (measured in mass of slurry per volume of air), t_{tx} is the duration of the spray release, ρ_{slurry} is the density of the transfer slurry, and $(\chi/Q')_{onsite,1189}$ is the atmospheric dispersion parameter at 100 meters specified in DOE Standard 1189, *Integration of Safety into the Design Process* [1], (3.5E-3 s/m^3). The dose to the co-located worker is then calculated by:

$$D_{onsite} = S \times C_U \times \left(\frac{\chi}{Q'}\right)_{onsite,1189} \times BR_{onsite} \times DCF_{onsite} \qquad (2)$$

where C_U is the concentration of uranium in the slurry, BR_{onsite} is the breathing rate for the co-located worker (at 100 meters), and DCF_{onsite} is the dose conversion factor per mass of uranium for the co-located worker.

To calculate the dose consequence to the public, the project team scales the onsite dose consequence with atmospheric dispersion, breathing rate, and dose conversion factor ratios as:

$$D_{offsite} = D_{onsite} \times \frac{\left(\frac{\chi}{Q'}\right)_{offsite}}{\left(\frac{\chi}{Q'}\right)_{onsite,ss}} \times \frac{BR_{offsite}}{BR_{onsite}} \times \frac{DCF_{offsite}}{DCF_{onsite}} \qquad (3)$$

where $(\chi/Q')_{onsite,ss}$ is the site specific atmospheric dispersion parameter at 100 meters (2.03E-2 s/m^3) and the subscript *offsite* refers to parameter values for the offsite receptor.

To technically justify the assumed aerosol concentration value at 100 meters, the project team used a comparison approach whereby the calculated dose consequences to the co-located worker from the fog model were compared to other established spray release methodologies [10]:

- DOE Handbook 3010-94, *Airborne Release Fractions/Rates and Respirable Fractions for Nonreactor Nuclear Facilities*, Figure 3-4 data for commercial hollow cone spray nozzles [11].

- Epstein and Plys, *Measured Drop Size Distribution with Cold Sprays Emanating From Small Leak Openings* [12].

- Dombrowski and Johns, *Aerodynamic Instability and Disintegration of Viscous Liquid Sheets* [13], using both the orifice area and hydraulic diameter models.

- Merrington and Richardson, *The Break-Up of Liquid Jets* [14].

- Pacific Northwest National Laboratory (PNNL) Correlation, *Large Scale Spray Release: Additional Aerosol Test Results* [15].

The comparison models predict airborne release fractions or parameters directly related to airborne release fraction (e.g., aerosol droplet generation rate or Sauter Mean Diameter). In order to compare with the assumed aerosol concentration used in the fog model approach, the project team employed the following relationship to calculate an aerosol concentration from a respirable airborne release fraction:

$$C_{100m} = \rho_{slurry} \times Q_{leak} \times (ARF \times RF) \times \left(\frac{\chi}{Q'}\right)_{onsite,1189} \quad (4)$$

where Q_{leak} is the volumetric flow rate of the spray and the term $ARF \times RF$ is the respirable airborne release fraction. In the comparison report, the project team used the DOE Standard 1189 value of $(\chi/Q')_{onsite,1189}$ to determine the 100 meter aerosol concentration predicted by the models listed above resulting in concentrations ranging from 0.90–11.9 mg/m^3. Based on these results, the project team concluded that reducing the assumed value of the aerosol concentration at 100 meters from 100 mg/m^3 to 12.5 mg/m^3 produces a reasonably conservative dose consequence to the co-located worker for a spray release. The Board's staff notes that the project team uses the site specific value of the atmospheric dispersion parameter to calculate offsite dose consequences and thus may be underestimating the offsite dose consequence by a factor of 5.8 (2.03E-2/3.5E-3).

Tables 1 and 2 list the dose consequences in the PDSA revisions due to an operational spray release and seismic spray release, respectively. In Revisions 1 and 2, the difference between the two accidents is the amount of sludge available for the spray accident. The engineered containers are rectangular in shape with a bottom "egg crate" section with eight sections that segregate material. For the operational spray release, the project team assumes that only the volume of one egg crate and the sludge above that egg crate that slumps down is available for release. For the seismic spray release, the project team assumes that the volume of one egg crate and all the sludge above the egg crate section can be released during the accident. Because the dose to the facility worker is high, the PDSA credits safety significant controls to prevent operational and seismic spray releases.

Table 1: Operational Spray Release Dose Consequences in PDSA Revisions

Location	Revision 0, Dose Consequence [rem TED]	Revision 1/2, Dose Consequence [rem TED]
Facility worker (qualitatively estimated)	> 100	70-90
Co-located worker (100 meters)	425	23
Onsite Public (Columbia River) (520 meters)	46	2.5
Offsite Public (10,070 meters)	0.9	0.048

Table 2: Seismic Spray Release Dose Consequences in PDSA Revisions

Location	Revision 0, Dose Consequence [rem TED]	Revision 1/2, Dose Consequence [rem TED]
Facility worker (qualitatively estimated)	> 100	160-220
Co-located worker (100 meters)	425	54
Onsite Public (Columbia River) (520 meters)	46	5.8
Offsite Public (10,070 meters)	0.9	0.11

Following the Board's staff's review of STP's spray release modeling, DOE-RL contracted with PNNL personnel to perform a technical review of the STP spray release methodology. On September 1, 2015, PNNL transmitted a report detailing the findings of its review [16]. PNNL personnel identified concerns with some of the inputs and assumptions used (many of which the Board's staff also had identified). They repeated the STP analysis with more conservative input values and assumptions and found the fog model bounded all the spray release models listed earlier except the Epstein and Plys model. PNNL personnel concluded that this result did not indicate non-conservatism of the STP model. They cited the limited number of experiments performed, issues with data measurements, and extrapolation of the Epstein and Plys correlation outside the range of the experiment as reasons why the Epstein and Plys results can be discounted and do not challenge the validity of the "fog model." The Board's staff team studied PNNL's assessment and generally agrees that the PNNL spray experiment is more technically defensible than the Epstein and Plys experiment. However, the staff team found agreement in the two out of the three test results between the PNNL and Epstein and Plys experimental correlations under similar test conditions. These results are shown in Figure 1. For this reason, the staff team continues to use the Epstein and Plys correlation (in its applicable testing range) in its additional analyses of the spray release accident to independently assess the risk to the public.

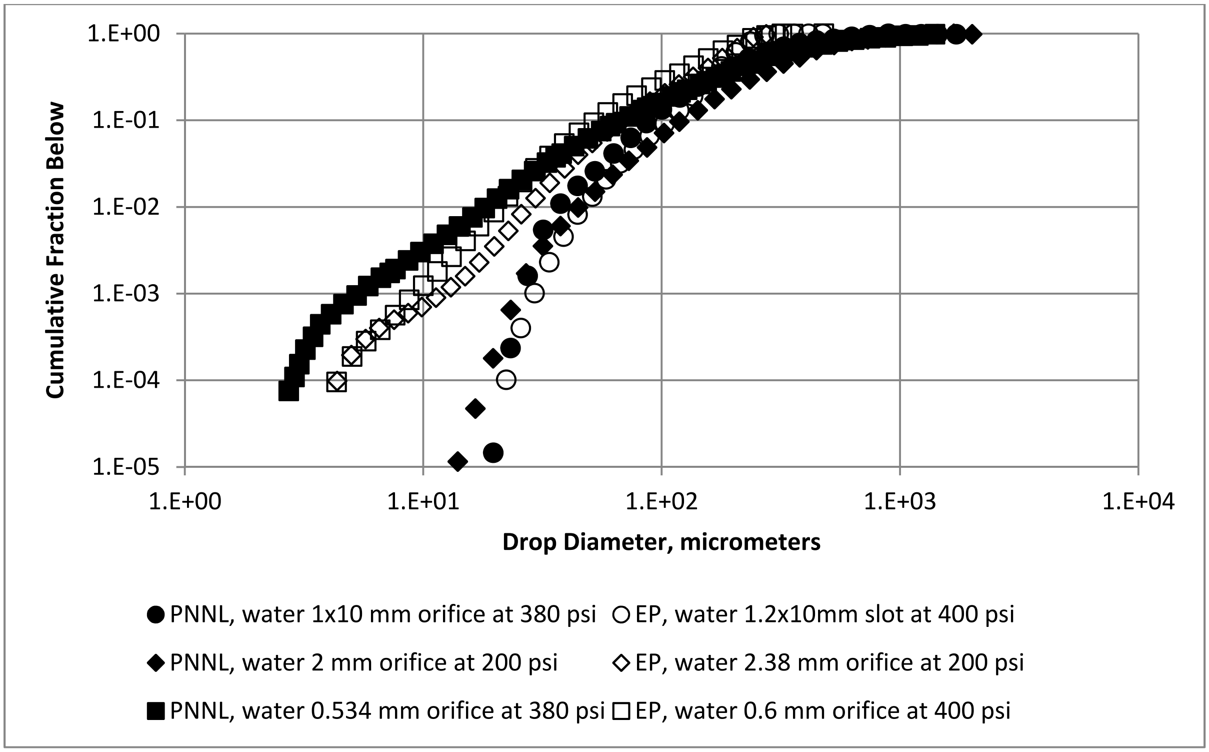

Figure 1: Comparison of spray test data between the PNNL and Epstein and Plys (EP) experimental correlations under similar conditions

3.2. INDEPENDENT MODELING APPROACH

The objective of the staff team's analysis was to independently assess the dose consequence to members of the public on the Columbia River due to a spray release accident. The staff team performed two calculations: one used a deterministic approach and the other used a probabilistic approach based on a range of input values. In both calculations, the PNNL and Epstein and Plys experimental correlations were used to model spray generation. The staff also considered two droplet evaporation models. The first evaporation model assumes the droplet remains quasi-spherical as it evaporates from source to receptor and also assumes a value for the packing fraction of the undissolved solid particles. The second evaporation model assumes that as the droplet evaporates, the undissolved solids form fractal packing configurations that lead to a dried solid agglomerate with voids.

It is important to note that both droplet evaporation models assume that the dried agglomerates do not break up into smaller particles during transport to the receptor. Consideration of agglomerate break-up due to shear forces for droplets larger than respirable size could lead to a larger population of respirable droplets and a greater dose consequence. This is important because in Hanford tank farm applications, dissolved salts in the tank waste will precipitate between the particles and act as a binder. For the STP application, the high salt content does not exist, and the dried agglomerates are expected to be more fragile and apt to break up. The staff's deterministic calculation used input values that were mainly derived from the STP ECRTS PDSA accident analysis, making it representative of the operational spray release accident. The staff's probabilistic calculation used input values derived from the STP

ECRTS design to develop appropriate minimum and maximum values. As such, the probabilistic calculation is representative of a general bounding spray release (without initiator specified), but can be compared to the seismic spray release accident in the PDSA Revisions 1 and 2.

The methodology used for the deterministic calculation is detailed in the Attachment to this report. Based on the input parameter values and analysis described in the Attachment, the spherical droplet evaporation model predicts a maximum respirable droplet size of 17.7 microns, and the fractal aggregate evaporation model predicts a maximum respirable droplet size of approximately 27 microns. Table 3 and Figure 2 present the calculated dose consequence at 520 meters (i.e., the receptor on the Columbia River) for the predicted maximum respirable droplet sizes. The results show that the STP model (i.e., the fog model) does not bound all correlations and measurements for generated droplet sizes greater than approximately 13.5 microns. However, none of the correlations or measurements predict dose consequences greater than the Evaluation Guideline for droplet sizes up to 30 microns.

Table 3: Radiological Dose Consequence at 520 Meters for the Deterministic Calculation

Model/Measurement	Dose at 520 m [rem TED]	
	17.7 µm (Spherical)	**26.97 µm (Fractal)**
STP Model, C_{100m} = 12.5 mg/m^3	2.71	2.71
PNNL Correlation, Area = 3.14 mm^2	0.43	1.18
PNNL Correlation, Area = 76 mm^2	5.37	14.74
Epstein Correlation, Area = 0.07 mm^2	0.05	0.14
Epstein Correlation, Area = 4.45 mm^2	3.31	8.68
PNNL, Large Scale (LS) Initial, W214, 1 mm hole	0.21	0.71
PNNL, LS Initial, W220, 2 mm hole	1.22	4.72
PNNL, LS Additional, W603, 2 mm hole	0.06	0.99
PNNL, LS Additional, W610, 1x10 mm slot	0.19	3.10
PNNL, LS Additional, W613, 1x20 mm slot	0.10	5.59
PNNL, LS Additional, W598, 1x76 mm slot	n/a*	n/a*
Epstein, 2.38 mm hole	2.06	7.64

* The experimental test case did not measure release fractions for those droplet sizes.

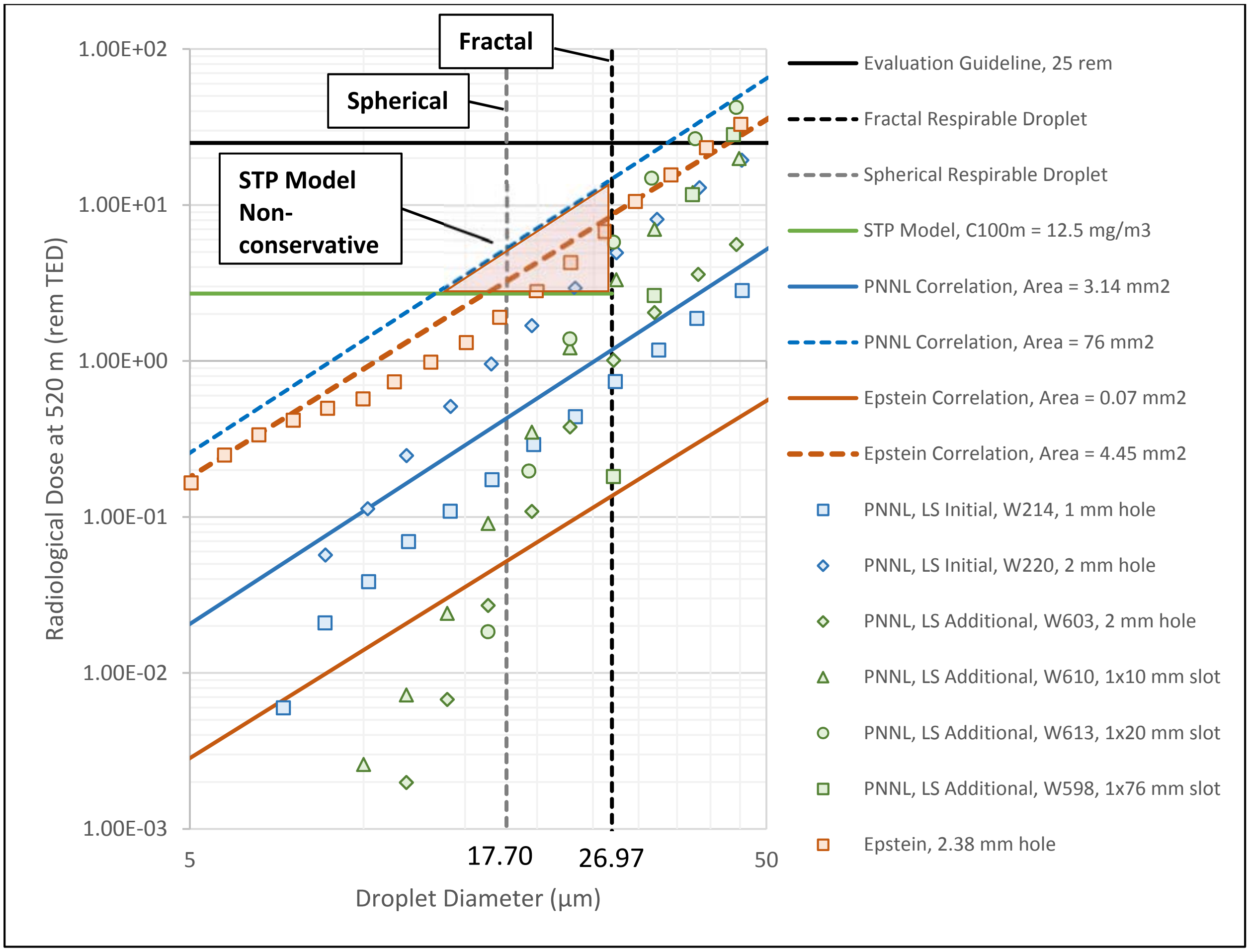

Figure 2: Radiological Dose Consequence at 520 Meters versus Droplet Diameter for the Deterministic Calculation

To assess the conservatism of the input values used in the STP ECRTS PDSA, the staff performed a probabilistic calculation. The methodology used for the probabilistic calculation is detailed in the Attachment to this report. Table 4 lists the statistical results of the calculations, and Figures 3 and 4 show a histogram of the dose consequence frequency for 500,000 samples for the spherical and fractal evaporation models, respectively. The staff's analysis predicted a 95th percentile dose consequence to members of the public on the Columbia River of 2.77 rem TED using the spherical evaporation model and 6.59 rem TED using the fractal evaporation model. The STP ECRTS PDSA methodology results (i.e., 2.5 rem TED for operational spray and 5.8 rem TED for seismic spray) are comparable to the staff's calculation results, but are slightly less than the results of the fractal evaporation model. The STP ECRTS PDSA identifies safety significant controls to prevent spray release accidents and includes defense-in-depth features that could mitigate the consequences.

Table 4: Dose Consequence at 520 meters for the Probabilistic Calculation

	Dose Consequence at 520 meters [rem TED]	
	Spherical Evaporation Model	**Fractal Evaporation Model**
Median	0.54	1.23
Mean	0.86	2.02
Standard Deviation	0.96	2.32
95th Percentile	2.77	6.59

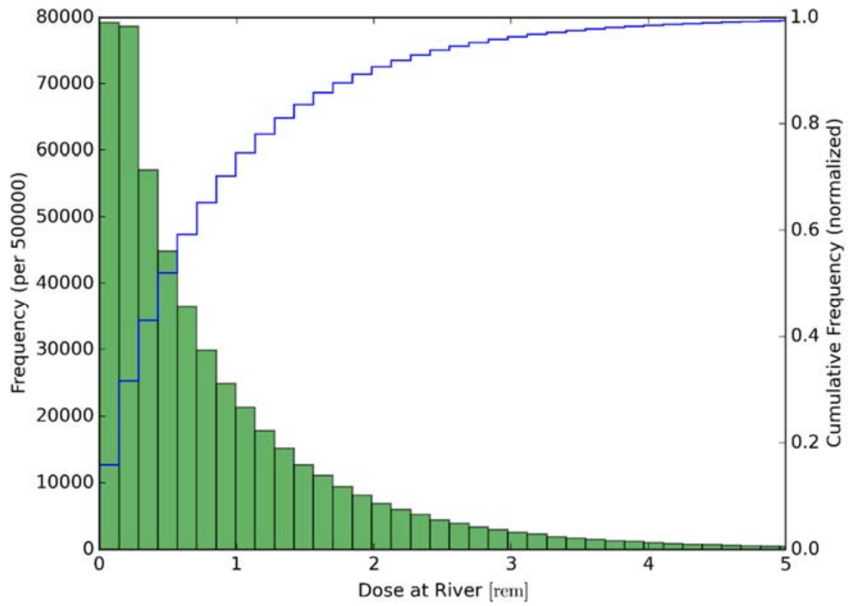

Figure 3: Histogram of Dose Consequence at 520 meters for the Spherical Evaporation Model

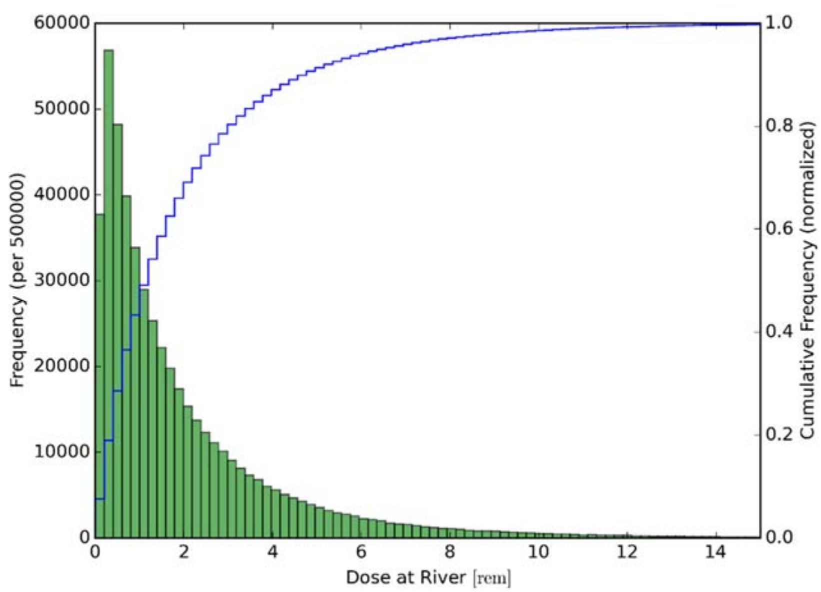

Figure 4: Histogram of Dose Consequence at 520 meters for the Fractal Evaporation Model

4. SLUDGE TREATMENT PROJECT SPRAY RELEASE ACCIDENT CONTROL STRATEGY

Figure 5 shows a simplified schematic of the sludge retrieval and transfer process. The sludge is retrieved using the Xago HydroLance™ tool to mobilize the sludge. The booster pump draws the resulting slurry of sludge and water through underwater transfer lines. Upstream of the booster pump, the slurry is transferred through an underwater hose (with rupture disk attached) to the ingress/egress assembly (through pipe-in-pipe construction). The slurry then flows from the ingress/egress assembly through the in-basin shielded hose chase to the horizontal shielded hose chase. The horizontal shielded hose chase is a concrete structure that connects the K West Basin and Annex. In the horizontal shielded hose chase, the slurry flows through a hose-in-hose transfer line into the transfer line service box (TLSB) in the Annex. The slurry is then transferred into the STSC.

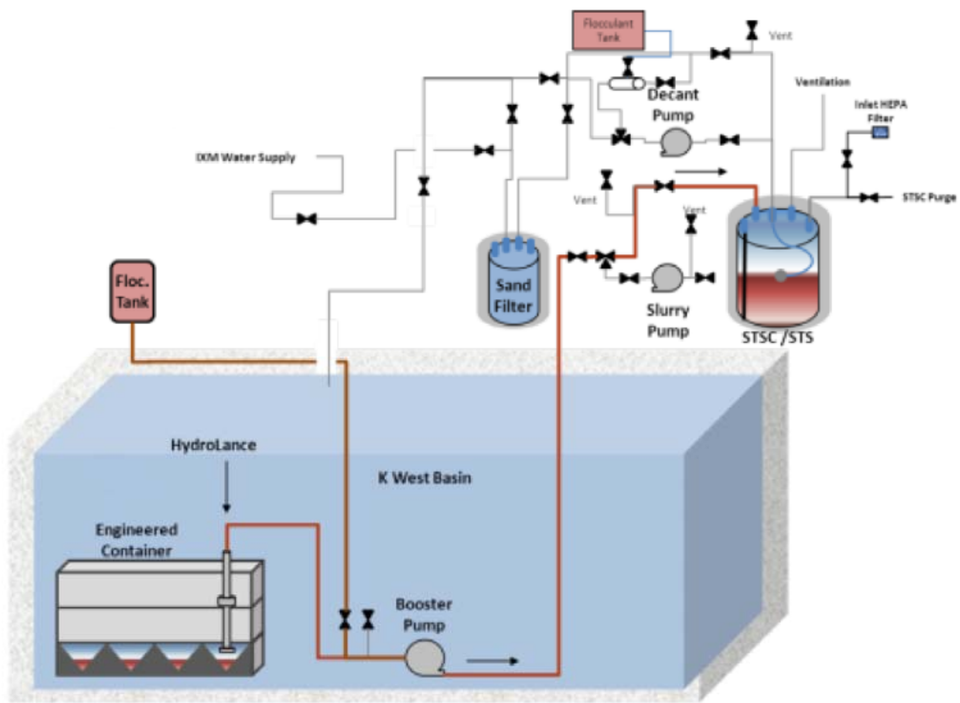

Figure 5: Simplified schematic of sludge retrieval and transfer process [17]

Because of significant dose consequences to the facility worker, the STP ECRTS PDSA Revision 2 identifies safety significant controls to prevent both operational and seismically induced spray releases. Table 5 lists the safety significant controls used to prevent and mitigate an operational spray release. Table 6 lists the safety significant controls used to prevent and mitigate a seismic spray release.

Table 5: Safety Significant Controls Credited with Preventing and Mitigating an Operational Spray Release

Control (SSC/SAC)	Safety Function
Above-water slurry transfer lines: • Inner pipe of the ingress/egress assembly slurry transfer line • Inner hose of the hose-in-hose slurry transfer line • Inner pipe of the coaxial connector slurry transfer line • Slurry transfer piping and hose within the TLSB	Prevent the spray release of slurry by maintaining integrity during sludge retrieval and transfer
Slurry transfer line rupture disk on the discharge side of the booster pump	Prevent the spray release of slurry by preventing over-pressurization of slurry transfer lines during sludge retrieval and transfer
Double-valve isolation	Prevent the spray release of slurry by preventing backflow into: • TLSB ion exchange module water supply lines • Overfill recovery line • Decant/flocculant recirculation line • In-basin flocculant addition line
Safety control panel ECRT-PNL-103	Prevent a spray release of slurry during sludge retrieval and transfer by protecting safety significant components
Slurry transfer line configuration SAC	Prevent the spray release of slurry during sludge retrieval and transfer by verifying proper slurry transfer line configuration prior to initiating a transfer
Work restriction SAC	Prevent the spray release of slurry during sludge retrieval and transfer by prohibiting work activities within the K West Basin with the potential to impact above-water slurry transfer lines during slurry transfers
Personnel access prohibition SAC	Mitigate facility worker consequences in the event of a spray release by prohibiting access to the K West Annex sludge loading bay during sludge retrieval and transfer
Basin water level SAC	Protect the hazard analysis assumption that transfer line failures underwater at the K West Basin do not result in airborne releases
Environmental control SAC	Prevent a spray release of slurry during sludge retrieval and transfer by ensuring safety significant components are operated within their evaluated temperature limits
Shield plate critical lift SAC	Prevent a spray release of slurry during sludge retrieval and transfer by preventing a shield plate drop

Table 6: Safety Significant Controls Credited with Preventing and Mitigating a Seismic Spray Release

Control (SSC/SAC)	Safety Function
• **Seismic shutdown switches** • **Safety shutdown interlock I-1**	Prevent a seismic-induced spray release of slurry by terminating slurry transfers during sludge retrieval and transfer upon detection of seismic motion
Safety control panel ECRT-PNL-103	Prevent a seismic-induced spray release of slurry during sludge retrieval and transfer by protecting safety significant components
Personnel access prohibition SAC	Mitigate facility worker consequences in the event of a spray release by prohibiting access to the K West Annex sludge loading bay during sludge retrieval and transfer

The controls listed in Tables 5 and 6 are credited with preventing and mitigating operational and seismic spray releases as the slurry is transferred from the engineered containers in the K West Basin to the STSCs. Based on the independent analysis of the Board's staff team, the unmitigated dose consequence to affected members of the public on the Columbia River during a general spray release accident is approximately 7 rem TED, if the slurry tends to form fractal aggregate droplets. This value does not exceed the Evaluation Guideline of 25 rem TED as defined in DOE Standard 3009-94 for classifying SSCs as safety class. DOE Standard 3009-94 states that the "value of 25 rem TED is not to be used as a 'hard' pass/fail level" and "unmitigated releases should be compared against the EG [Evaluation Guideline] to determine whether they challenge the EG, rather than exceed it." DOE Standard 1189-2008, *Integration of Safety into the Design Process*, defines "challenging the EG" as unmitigated dose consequences greater than 5 rem TED but less than 25 rem TED. For unmitigated dose consequences in this range, DOE Standard 1189-2008 states that "SC [safety class] designation should be considered, and the rationale for the decision to classify an SSC as SC or not should be explained and justified."

The staff's probabilistic analysis shows that after taking into account uncertainties, the calculated dose consequences remain below the Evaluation Guideline. Based on this analysis and a review of the control strategy, the staff team believes that the control set credited in the ECRTS PDSA Revision 2 is adequate to protect members of the public on the Columbia River and surrounding public lands. Further, the design of the retrieval and transfer system has many defense-in-depth features that are not explicitly credited, but would mitigate the dose consequences due to a spray release. For example, above the K West Basin water, the slurry is transferred in pipe-in-pipe or hose-in-hose transfer lines. The primary inner pipe/hose is credited as safety significant for preventing a spray release. The secondary outer pipe is not credited, but would serve to reduce the atomization efficiency of a spray emanating from the inner pipe, thus mitigating dose. The staff team notes that DOE Order 420.1C, *Facility Safety*, requires application of the same commercial standard (ASME B31.3, *Process Piping*) equally to both safety class and safety significant piping systems [18]. The concrete horizontal shielded hose chase also would mitigate the accident in the same manner. Further, the safety significant burst disk is credited with preventing a spray release due to over-pressurization, but also serves to reduce the maximum pressure at which a spray release could develop. The staff used a maximum pressure of 200 psig in its probabilistic calculation. If the maximum pressure is limited to 115 psig (i.e., the burst disk rupture pressure), the mitigated 95th percentile dose to members of the public on the Columbia River would be 2.25 rem TED for the fractal aggregate model.

5. CONCLUSIONS

In an August 21, 2015, letter, the Board expressed concern with the removal of a SAC used to control public access to the Columbia River from the ECRTS PDSA. The Board requested a report from DOE describing DOE's position on, and technical basis for, controlling Columbia River access and protecting potentially affected members of the public from spray release accidents during slurry transfers. The DOE report concluded that the control strategy defined in ECRTS PDSA Revision 1 was adequate to protect members of the public on the Columbia River and that the SAC was no longer needed.

Accidental spray release modeling is complex. The Board's staff performed calculations to independently determine the dose consequence to members of the public on the Columbia River. Based on the calculation results and a review of the ECRTS control strategy, the staff believes that the control set adequately protects the public and workers from spray release hazards during STP operations.

Attachment
Independent Analysis of STP Spray Release Accidents

Introduction. A spray release is one of the major hazards identified in the Engineered Container Retrieval and Transfer System (ECRTS) preliminary documented safety analysis (PDSA). This accident can be initiated by operational events, a facility fire, natural phenomena hazards, or external events.

The spray release accident scenario is based on an undetected breach of primary containment that occurs while sludge is being transferred from the engineered container in the K West Basin to the sludge transport and storage containers (STSC) in the sludge loading bay located in the K West Basin Annex. The amount of slurry that is released and aerosolized depends on the size of the breach, the fluid pressure, the material properties of the fluid, the duration of the release, and the event initiator. To avoid the complexity and uncertainty associated with modeling a spray release, the Sludge Treatment Project (STP) assumed a slurry aerosol concentration resulting in a correlation-independent approach (i.e., the "fog model") to calculate the dose consequence [6, 10].

To evaluate the dose consequence associated with a spray release accident during sludge transfer at STP, the Defense Nuclear Facilities Safety Board's (Board) staff performed two calculations. The first used a deterministic approach, comparing the results of the "fog model" to recent experimental correlations and measurements. The second used a probabilistic approach based on a range of input parameters. The staff used the Pacific Northwest National Laboratory (PNNL) [15] and Epstein and Plys [12] correlations in both calculations. A summary of the main results of each calculation is provided below. Appendix A of this Attachment details the methodology of the deterministic calculation. Appendix B of this Attachment details the methodology of the probabilistic calculation.

General Analysis Methodology. For a spray release accident, the general approach to calculating the dose consequence to a receptor (potentially affected member of the public) is:

- Determine the size of the spray droplet that is respirable at the receptor based on the droplet's aerodynamic equivalent diameter. The droplet size will depend on the liquid density, solids density, and solids volume fraction.

- Determine the size of the spray droplet generated at the source that could evaporate down to a respirable size at the receptor. The extent of evaporation will depend on the liquid properties and the liquid's propensity to form spherical or fractal-like droplets.

- Apply a spray droplet size distribution correlation to determine the number of respirable droplets generated at the source. The product of the number of droplets generated per unit time, the amount of radiological material in each droplet, and the total accident time yields the radiological source term.

- Calculate the dose consequence to the receptor through the inhalation pathway by considering atmospheric dispersion, breathing rate, and dose conversion factor.

General Assumptions. The following assumptions are made in both calculations:

1. All radioactive solid particles are assumed to be contained in liquid droplets exiting the discharge orifice.

2. The STP sludge/water slurry behaves like a Newtonian fluid.

3. Liquid spray correlations are applicable to low solids slurries.

4. The 95th percentile value in a probabilistic calculation represents a conservative result.

5. Deposition of the respirable droplets as they travel from source material to the receptor is not considered (i.e., all respirable droplets generated at the source make their way to the receptor).

6. Two droplet evaporation models are considered. One assumes the droplet evaporates into a spherical agglomerate of solid particles, water, and small air voids. The other assumes the droplet evaporates into a fractal-shaped agglomerate with solids particles, water, and large air voids.

Results of the Deterministic Calculation. Based on the input parameter values and analysis described in Table AA-1 of Appendix A of this Attachment, the spherical droplet evaporation model predicts a maximum respirable droplet size of 17.7 microns, and the fractal aggregate evaporation model predicts a maximum respirable droplet size of approximately 27 microns. Table A-1 lists the calculated dose consequence at 520 meters (i.e., the receptor on the Columbia River) for the predicted maximum respirable droplet sizes. For entries labeled "n/a," the experimental test case did not measure release fractions for those droplet sizes. These results also are plotted in Figure A-1. In Figure A-1, a solid, black, horizontal line is drawn to show the Evaluation Guideline of 25 rem total effective dose (TED) as defined in Department of Energy (DOE) Standard 3009-94, *Preparation Guide for U.S. Department of Energy Nonreactor Nuclear Facility Documented Safety Analyses* [2]. A dashed, black, vertical line represents the maximum respirable droplet size predicted by the fractal evaporation model. A dashed, grey, vertical line represents the maximum respirable droplet size predicted by the spherical evaporation model.

In this calculation, the "fog model" predicts a radiological dose at 520 meters of 2.71 rem TED. This value is slightly greater than the 2.5 rem TED listed in the STP ECRTS PDSA. The difference is due to the assumed slurry solids volume fraction. Of note, the "fog model" predicted dose consequence does not depend on droplet size because the assumed aerosol concentration of the slurry is fixed. Further, in the "fog model," the assumed aerosol concentration is for respirable particles only. It is therefore only applicable in the respirable droplet range. For droplet sizes of 10 microns, the fog model bounds the dose consequence predictions of the correlations and measurements. For droplet sizes greater than approximately 13.5 microns, the PNNL correlation with orifice area of 76 mm^2 exceeds the "fog model" and bounds all other correlations and measurements. For respirable droplet sizes assuming spherical droplets (17.70 microns), the fog model bounds all measurements, but is exceeded by both correlations with their largest orifice area. For respirable droplet sizes assuming fractal-like droplets (26.97 microns), the fog model only bounds the correlations with smaller orifice areas and smaller orifice area measurements. None of the correlations or measurements predict dose consequences greater than the Evaluation Guideline of 25 rem TED up to approximately 30 microns.

It is also important to note the large difference between the PNNL Large Scale (LS) Initial and Additional measurements results for the 2 mm hole case. The difference between the two cases is due to measurement equipment change (i.e., 100 mm vs. 500 mm lens). PNNL could not fully determine the nature of this difference. Given that the PNNL correlation with larger area bounds all the measurements, especially in the range of interest (i.e., 10–30 microns), the large difference between these two measurements does not alter the conclusions that can be drawn from this calculation.

Table A-1: Radiological Dose Consequence at 520 Meters for Droplet Sizes of Interest

Model/Measurement	**Dose at 520 m [rem TED]**	
	17.7 µm (Spherical)	**26.97 µm (Fractal)**
STP Model, C_{100m} = 12.5 mg/m^3	2.71	2.71
PNNL Correlation, Area = 3.14 mm^2	0.43	1.18
PNNL Correlation, Area = 76 mm^2	5.37	14.74
Epstein Correlation, Area = 0.07 mm^2	0.05	0.14
Epstein Correlation, Area = 4.45 mm^2	3.31	8.68
PNNL, Large Scale (LS Initial), W214, 1 mm hole	0.21	0.71
PNNL, LS Initial, W220, 2 mm hole	1.22	4.72
PNNL, LS Additional, W603, 2 mm hole	0.06	0.99
PNNL, LS Additional, W610, 1x10 mm slot	0.19	3.10
PNNL, LS Additional, W613, 1x20 mm slot	0.10	5.59
PNNL, LS Additional, W598, 1x76 mm slot	n/a*	n/a*
Epstein, 2.38 mm hole	2.06	7.64

* The experimental test case did not measure release fractions for those droplet sizes.

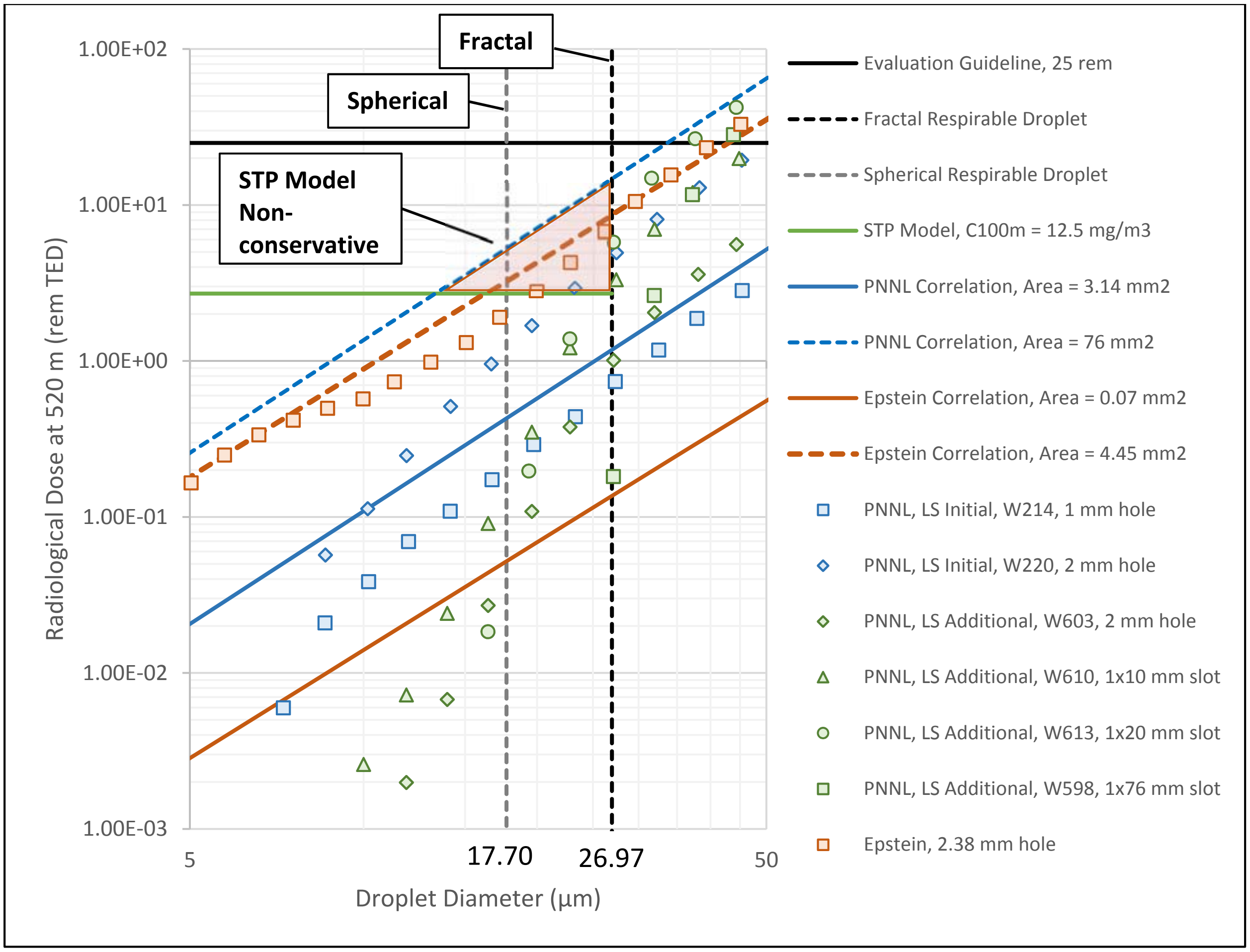

Figure A-1: Radiological Dose Consequence at 520 Meters versus Droplet Diameter

Results of the Probabilistic Calculation. Table A-2 lists the statistical results of the calculations where all parameters listed in Table AB-2 were sampled. Figures A-2 and A-3 show a histogram of the dose consequence frequency for 500,000 samples for the spherical and fractal evaporation models, respectively. A sensitivity study was performed with 50,000 and 5,000,000 samples; the 95th percentile dose varied by less than 0.1 percent. The blue line represents the normalized cumulative frequency. DOE Standard 3009-94 states, "The unmitigated release calculation represents a theoretical limit to scenario consequences assuming that all safety features have failed, so that the physical release potential of a given process or operation is conservatively estimated" [2]. Typically, the 95th percentile result is used to provide a conservative estimate for probabilistic calculations. The 95th percentile dose consequences predicted by the spherical and fractal evaporation models are 2.77 rem TED and 6.59 rem TED, respectively. Both evaporation models predict dose consequences below the Evaluation Guideline. The 95th percentile dose consequence from the spherical evaporation model is comparable to the 2.5 rem TED value determined by STP analysts using the correlation independent approach (i.e., the "fog model").

Table A-2: Dose Consequence at 520 meters / Columbia River

	Dose Consequence at 520 meters [rem TED]	
	Spherical Evaporation Model	**Fractal Evaporation Model**
Median	0.54	1.23
Mean	0.86	2.02
Standard Deviation	0.96	2.32
95th Percentile	2.77	6.59

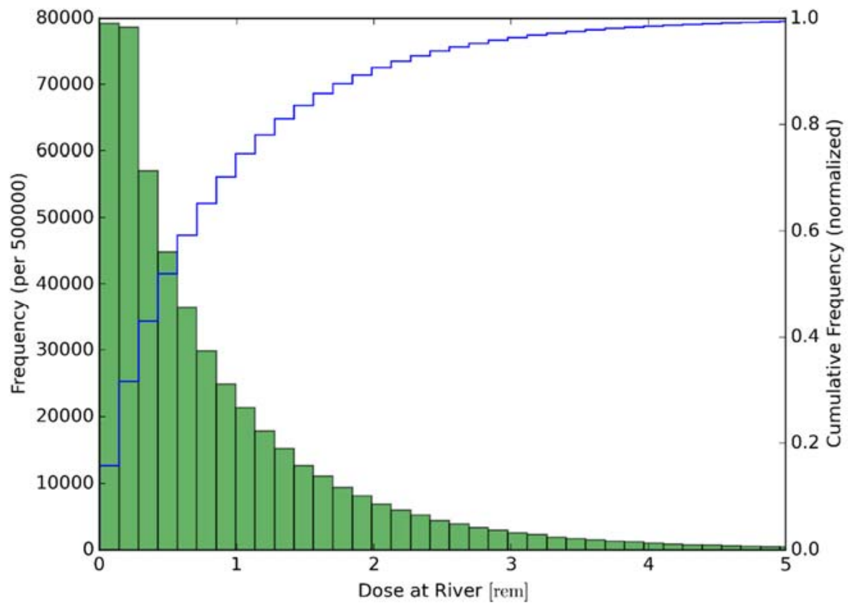

Figure A-2: Histogram of Dose Consequence at 520 meters for the Spherical Evaporation Model

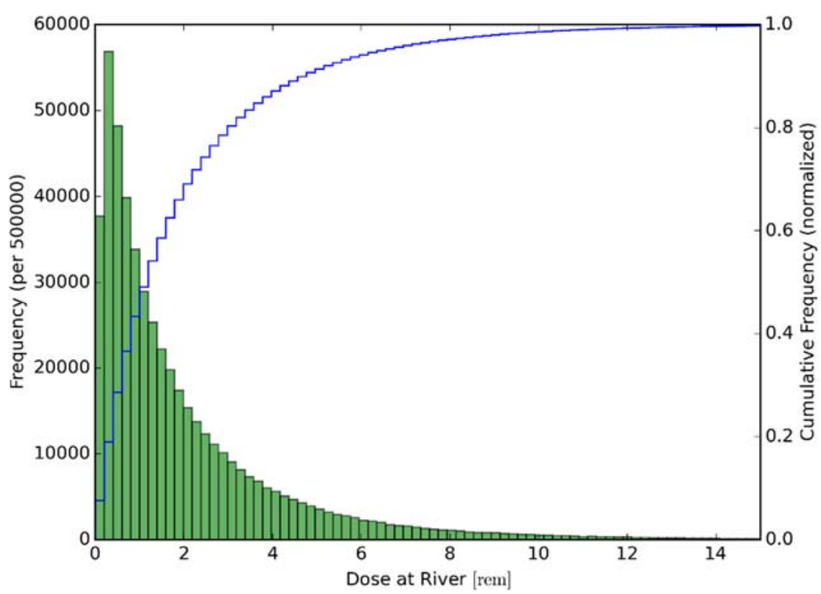

Figure A-3: Histogram of Dose Consequence at 520 meters for the Fractal Evaporation Model

Summary and Conclusions. The objective of the staff team's analysis was to independently assess the dose consequence to a receptor on the Columbia River due to a spray release accident. The staff team performed two calculations, one used a deterministic approach, the other a probabilistic approach based on a range of input values. In both calculations, the PNNL and Epstein and Plys experimental correlations were used to model spray generation; two droplet evaporation models were considered. The deterministic calculation used input values that were mainly derived from the STP ECRTS PDSA accident analysis. The probabilistic calculation used input values derived from the STP ECRTS design to develop appropriate minimum and maximum values.

The results of the deterministic calculation show that the STP model does not bound all correlations and measurements for droplet sizes greater than approximately 13.5 microns. However, none of the correlations or measurements predict dose consequences greater than the Evaluation Guideline for droplet sizes up to 30 microns.

To assess the margin of conservatism in the input values used in the STP ECRTS PDSA, the staff performed a probabilistic calculation. The staff's analysis predicted 95th percentile dose consequence to the public receptor on the Columbia River of 2.77 rem TED using a spherical evaporation model and 6.59 rem TED using a fractal evaporation model. The STP ECRTS PDSA methodology results (i.e., 2.5 rem TED) are comparable to the spherical evaporation model results, but are exceeded by the predicted results of the fractal evaporation model. However, the dose consequence predicted by the fractal evaporation model does not exceed the Evaluation Guideline. The STP ECRTS PDSA identifies safety-significant controls to prevent this accident and has defense-in-depth features that would mitigate the consequence of this accident.

Appendix A
Methodology for the Staff's Deterministic Calculation of an STP Spray Release Accident

This appendix details the deterministic calculation of dose consequence to a receptor (member of the public) on the Columbia River due to a spray release during sludge transfer.

Input Parameters. Most of the input parameter values used for this calculation are extracted from the Sludge Treatment Project (STP) Engineered Container Retrieval and Transfer System (ECRTS) preliminary documented safety analysis (PDSA) and supporting report [6, 10]. The Defense Nuclear Facilities Safety Board's (Board) staff team researched additional values for key parameters. Input parameters common to the models used in this calculation and the basis for their values are listed in Table AA-1.

Table AA-1: Common Input Parameter Values

Parameter	Variable	Unit	Value	Basis
Differential pressure across breach	Δp	psi	200	[10], Table 6 & Attach.
Pump flow rate	L	gpm	70	[6], Page 3-44
Discharge coefficient	C_d	-	0.74	[10], Table 6 & Attach.
Sludge volume	V_s	m^3	1.11	[6], Page 3-45
Sludge solid volume fraction	α_s	-	0.45	[10], Table 6 & Attach.
Sludge solids density	ρ_s	kg/m^3	5,000	[10], Table 6 & Attach.
Water density	ρ_l	kg/m^3	1,000	[10], Table 6 & Attach.
Slurry (mixture) solid volume fraction	α_m	-	0.044†	[6], Page 3-40
Breathing rate	BR	m^3/s	3.29E-04	[6], Table 3-4
Site specific atmospheric dispersion, 100 m	$\left(\frac{\chi}{Q'}\right)_{100m}$	s/m^3	2.03E-02	[6], Table 3-3
Site specific atmospheric dispersion, 520 m	$\left(\frac{\chi}{Q'}\right)_{520m}$	s/m^3	2.36E-03	[6], Table 3-3
Dose conversion factor by volume of sludge	DCF	rem/m^3	2.65E+10	[6], Table 3-6
Sludge (solids) volume fraction in evaporated droplet at receptor	$\alpha_{s,R}$	-	0.55	[16], Page 10
Droplet dynamic shape factor	κ	-	1.60	[16], Page 10
Fraction of liquid remaining in evaporated droplet	x	-	0.00	[16], Page 10
Density of air	ρ_a	kg/m^3	1.20	[19], Appendix A
Aerodynamic equivalent droplet diameter at receptor	d_{aed}	µm	10	[20], Page 1-5
Diameter of solid in droplet	d_s	µm	0.1	See Section 3
Rosin-Rammler shaper parameter	q	-	2.30	[10], Page 17
Breach area	A	mm^2	varies	See Section 3

† In the PDSA, the analysts choose a value of 0.075 for the slurry solids volume fraction, corresponding to an accident time of one hour for a seismic spray release. Lower values will increase the accident time and the respirable droplet diameter at the source. During testing, the Xago removal tool had a nominal retrieval composition of 0.044 slurry solids volume fraction.

General Parameters. The analysis begins by calculating additional general input parameters for the droplet evaporation models and spray correlations.

The volume of the slurry (i.e., mixture of transferred sludge and water) that is transferred is based on the solid volume fraction in the sludge and slurry:

$$V_m = \frac{\alpha_s}{\alpha_m} \times V_s \qquad \text{(AA-1)}$$

where α_s is the solid volume fraction in the sludge, α_m is the solid volume fraction in the slurry, and V_s is the volume of sludge transferred.

The density of the slurry is also a function of the solid volume fraction of the sludge and slurry:

$$\rho_m = \alpha_m \rho_s + (1 - \alpha_m)\rho_l \qquad \text{(AA-2)}$$

where ρ_s is the density of the sludge and ρ_l is the density of the transfer liquid (i.e., water).

The time it takes to transfer the slurry is a function of the volume of slurry transferred and the transfer flow rate:

$$t_{tx} = \frac{V_m}{L} \qquad \text{(AA-3)}$$

where L is the transfer flow rate.

The velocity of the slurry exiting a breach is determined by applying Bernoulli's principle across the orifice:

$$U = C_d \sqrt{\frac{2\Delta p}{\rho_m}} \qquad \text{(AA-4)}$$

where C_d is the orifice discharge coefficient and Δp is the differential pressure between the spray and atmosphere. The volumetric flow rate of the spray out of the leak is then:

$$Q = U \times A \qquad \text{(AA-5)}$$

where A is the cross-sectional area of the breach/orifice.

Droplet Evaporation Models. An important parameter for droplet size distribution correlations is the droplet size of interest. For radiological dose consequence calculations, the diameter of the droplet at the source that could evaporate down to a respirable droplet size at the receptor is needed. For this calculation, two droplet evaporation models are considered.

Spherical Evaporation Model—The first model is used in the STP ECRTS spray release comparison report [10]. A spherical water droplet carrying monodisperse spherical solid particles is assumed. Assuming a packing fraction of the solid particles in the evaporated droplet at the receptor ($\alpha_{s,R}$), the evaporated droplet diameter is:

$$\rho_{d,R} = \alpha_{s,R}\rho_s + \left(1 - \alpha_{s,R}\right)[x\rho_l + (1 - x)\rho_a] \tag{AA-6}$$

where x is the fraction of liquid remaining in the evaporated droplet (i.e., the fraction of the non-solids volume of the droplet) and ρ_a is the density of air.

Based on conservation of mass, the maximum respirable droplet diameter at the source is:

$$d_{r,S} = \left[d_{aed}\sqrt{\frac{\kappa\rho_l}{\rho_{d,R}}}\right] \times \sqrt[3]{\frac{\alpha_{s,R}}{\alpha_m}} \tag{AA-7}$$

where d_{aed} is the aerodynamic equivalent diameter and κ is the dynamic shape factor of the droplet.

Fractal Aggregate Evaporation Model—Depending on the makeup of the slurry, spray droplets may evaporate into agglomerate structures with large voids. Lind et al. [21] present equations that described the aerodynamic diameter of dried solid agglomerates in a fractal packing configuration. Their equations account for potential voids within the dried solid agglomerate. The aerodynamic droplet diameter is:

$$d_{aed} = d_s\left(\frac{\rho_s}{\rho_l\kappa}\right)^{\frac{1}{2}}\left(\frac{d_m}{d_s}\right)^{\frac{D_f-1}{2}} \tag{AA-8}$$

and the number of solid particles is:

$$n_p = \left(\frac{d_m}{d_s}\right)^{D_f} \tag{AA-9}$$

where d_s is the diameter of the solid particles in the dried aerosol, d_m is the mobility diameter of the dried aerosol, and D_f is the fractal dimension of the dried aerosol. If the number of solid particles within a droplet are assumed to be dispersed homogeneously in the droplet and there is no coalescence, the number of solid particles in the droplet at the source can be determined by:

$$n_p = \alpha_m\left(\frac{d_{r,S}}{d_s}\right)^3 \tag{AA-10}$$

Setting Equation AA-9 equal to AA-10 and substituting into Equation AA-8 yields:

$$d_{r,S} = \frac{d_s}{\alpha_m^{1/3}} \left[\left(\frac{\kappa \rho_l}{\rho_s} \right)^{1/3} \left(\frac{d_{aed}}{d_s} \right)^{2/3} \right]^{\frac{D_f}{D_f - 1}} \quad \text{(AA-11)}$$

From Equations AA-9 and AA-10, the mobility diameter is:

$$d_m = \alpha_m^{\frac{1}{D_f}} d_{r,S}^{\frac{3}{D_f}} d_s^{1-\frac{3}{D_f}} \quad \text{(AA-12)}$$

Setting the mobility diameter to the respirable droplet diameter at the source, yields:

$$D_f = 3 + \frac{\ln(\alpha_m)}{\ln\left(d_{r,S}\right) - \ln(d_s)} \quad \text{(AA-13)}$$

To solve for the maximum respirable droplet diameter, an initial guess is made for the fractal dimension. Equation AA-11 is then solved and the result is used to calculate the fractal dimension using Equation AA-13. This process is repeated until the maximum respirable droplet diameter and fractal dimension do not change significantly between iterations.

The fractal aggregate model requires knowledge of the solids particle size in the droplet. Table 4-8a of Reference [22] gives the particle size distribution of SCS-CON-230 sludge. Approximately 28 percent of the sludge solid particles are less than five microns in size. For the inputs in Table AA-1, Equation AA-13 yields fractal dimensions near one for solid particle sizes greater than three microns. Wells et al. [23] provide a summary of measured fractal dimensions for Hanford tank waste; fractal dimensions tend to be in the range of 1.6–2.5. Assumed solid particle sizes of 0.1–2.5 microns yield fractal dimensions in the range of 1.6–2.5. For these solid particle sizes, Equation AA-11 is fairly insensitive and yields approximately the same maximum respirable droplet size. Therefore, a solid particle size of 1 micron is assumed in this calculation, yielding a fractal dimension of approximately 2.

Spray Models. In this calculation, the correlation-independent spray release methodology used in the STP ECRTS PDSA is compared to Pacific Northwest National Laboratory (PNNL) [15] and Epstein and Plys [12] correlations and measurements. The methodologies for predicting the cumulative airborne release fraction (ARF) are shown below. In the following equations, the droplet diameter of interest (d_d) is used. To determine cumulative respirable airborne release fraction, substitute $d_d = d_{r,S}$.

STP Fog Model—The STP fog model approach assumes an aerosolized slurry concentration at 100 meters from the source of $C_{100m} = 12.5$ mg/m^3. The cumulative airborne release fraction is:

$$ARF = \frac{C_{100m}}{\rho_m \times Q \times \left(\frac{\chi}{Q'}\right)_{100m}} \quad \text{(AA-14)}$$

where $\left(\frac{\chi}{Q'}\right)_{100m}$ is the atmospheric dispersion parameter at 100 meters.

PNNL Correlation—In 2013, PNNL developed an empirical power-law correlation for calculating the generation rate of airborne droplets from a spray based on extensive testing. The cumulative airborne release fraction is:

$$ARF = \frac{3.26 \times 10^{-16}(A^{0.793})(\Delta p^{2.18})(d_d^{2.40})}{Q} \tag{AA-15}$$

where A is in units of millimeters, Δp is in units of psig, and d_d is in units of µm.

In the analysis, the PNNL correlation is evaluated at two breach areas, 3.14 mm^2 and 76 mm^2. These values represent the minimum and maximum breach areas tested in the experimental studies that were used to derive the correlation.

Epstein and Plys Correlation—In 2006, Epstein and Plys developed a power-law correlation for Sauter Mean Diameter (SMD) of the spray droplets based on in-spray droplet size measurements. Tests were conducted with water sprays between 180 psig and 600 psig and a range of orifice sizes from 0.07 mm^2 and 12 mm^2. The SMD is:

$$SMD = \frac{6.39 \times 10^{-3}}{(\Delta p)^{0.279}} \tag{AA-16}$$

where Δp is in units of Pascals and SMD is in units of meters.

To determine the cumulative airborne release fraction, a Rosin-Rammler distribution is assumed:

$$ARF = 1 - exp\left[-\left(\frac{d_d}{X}\right)^q\right] \tag{AA-17}$$

where q is the Rosin-Rammler shape parameter and $X = SMD \times \Gamma(1 - 1/q)$, Γ denotes the gamma function:

$$\Gamma(t) = \int_0^\infty x^{t-1}e^{-x}dx \tag{AA-18}$$

In the analysis, the Epstein and Plys correlation is evaluated at two breach areas, 0.07 mm^2 and 4.45 mm^2. These values represent the minimum and maximum breach areas tested in the experimental studies that were used to derive the correlation. Epstein and Plys provided a separate correlation for the 12 mm^2 test. The Rosin-Rammler shape parameter for the 12 mm^2 case is 3.47 versus 2.3 for the other test cases. Because the shape parameter is much larger in the 12 mm^2 case, the dose consequence predictions are bounded by the 4.45 mm^2 case.

Spray Measurements. Several of the test cases performed in the PNNL and Epstein and Plys experiments were similar to the conditions expected in a STP spray release. In this calculation, these cases were used to predict the radiological dose consequence for comparison with the fog model and correlations. The following test cases were used in this calculation:

- PNNL Large-Scale Initial [24], Test W214, Figure 8.31, 1 mm hole
- PNNL Large-Scale Initial [24], Test W220, Figure 8.30, 2 mm hole
- PNNL Large-Scale Additional [15], Test W603, Page B.373, 2 mm hole
- PNNL Large-Scale Additional [15], Test W610, Page B.379, 1 mm x 10 mm slot
- PNNL Large-Scale Additional [15], Test W613, Page B.383, 1 mm x 20 mm slot
- PNNL Large-Scale Additional [15], Test W598, Page B.388, 1 mm x 76 mm slot
- Epstein and Plys [12], Figure 5-12, 2.38 mm hole

All test cases used in this calculation were performed with a pressure differential of 200 psig, and droplet size measurements were taken in-spray. For all test cases, airborne release fraction is plotted versus droplet diameter. The numerical data were extracted from the figures using WebPlotDigitizer [25], an open source software developed to accurately extract data from a variety of plot types.

To determine the cumulative release fraction at the droplet diameter of interest, linear interpolation was used:

$$ARF(d_d) = ARF_1 + \frac{ARF_2 - ARF_1}{d_{d,2} - d_{d,1}}\left(d_d - d_{d,1}\right) \qquad \text{(AA-19)}$$

where the subscripts 1 and 2 denote known values for ARF and d_d less than and greater than the droplet size of interest.

Radiological Dose Consequence. The radiological dose consequence due to inhalation of the spray can be determined from the source term and consideration of the atmospheric dispersion, breathing rate, and dose conversion factor. The radiological dose consequence is:

$$D_x = [Q \times t_{tx} \times ARF \times RF] \times \left(\frac{\chi}{Q'}\right)_x \times BR \times DCF \times \left(\frac{\alpha_m}{\alpha_s}\right) \qquad \text{(AA-20)}$$

In Equation (AA-17), if ARF is chosen at $d_d = d_{r,S}$, then $RF = 1$.

Appendix B
Methodology for the Staff's Probabilistic Calculation of an STP Spray Release Accident

This appendix details the probabilistic calculation of dose consequence to a receptor (member of the public) on the Columbia River due to a spray release during transfer of sludge.

Input Parameters. Most of the input parameter values used for this calculation are extracted from the Sludge Treatment Project (STP) Engineered Container Retrieval and Transfer System (ECRTS) design documents. The Defense Nuclear Facilities Safety Board's (Board) staff team researched additional values for key parameters. Table AB-1 lists input parameters with fixed values. Table AB-2 lists input parameters that were varied and the minimum and maximum values assumed for each parameter. Appendix C provides a discussion on the selection of the minimum and maximum values assumed.

Table AB-1: Fixed Input Parameters

Parameter	Variable	Unit	Value	Basis
Number of samples	N_s	-	500,000	
Air density	ρ_a	kg/m^3	1.20	[19], Appendix A
Water density	ρ_l	kg/m^3	1,000	[10], Table 6
Transfer flow rate	L	gpm	70	[6], Page 3-44
Aerodynamic equivalent droplet diameter	d_{aed}	µm	10	[20], Page 1-5
Breathing rate	BR	m^3/s	3.29E-4	[6], Table 3-4
Site specific atmospheric dispersion factor without plume meander, 520 m	$\left(\frac{\chi}{Q'}\right)_{noPM}$	s/m^3	2.36E-3	[6], Table 3-3
Site specific atmospheric dispersion factor without plume meander, 520 m	$\left(\frac{\chi}{Q'}\right)_{PM}$	s/m^3	5.66E-4	[6], Table 3-3

Table AB-2: Varied Input Parameters

Parameter	Variable	Unit	Minimum Value	Maximum Value
Differential pressure across breach	Δp	psi	50	200
Discharge coefficient	C_d	-	0.50	0.80
Discharge area	A	mm^2	0.07	76
Sludge volume	V_s	m^3	1.11	2.64
Sludge solid volume fraction	α_s	-	0.27	0.45
Sludge density	ρ_{sludge}	kg/m^3	2000	2800
Slurry (mixture) solid volume fraction	α_m	-	0.04	0.15
Dose conversion factor by volume of sludge	DCF	rem/m^3	1.75E10	2.65E10
Sludge (solids) volume fraction in droplet at receptor	$\alpha_{s,R}$	-	0.05	0.95
Liquid fraction remaining in evaporated droplet	x	-	0.00	1.00
Droplet dynamic shape factor	κ	-	1.00	2.00

Analysis Methodology. This calculation uses the same analysis methodology as the deterministic calculation (Equations AA-1–AA-20), but instead of using static values, the input parameters listed in Table AB-2 are varied in each sample. Because no information on the distribution of the input parameters is available, the varied input parameters were randomly sampled using a uniform distribution based on the minimum and maximum assumed values.

Because of the varied approach, two important differences exist between the deterministic and probabilistic calculations. These differences are discussed below.

Correlation Choice by Area. The Pacific Northwest National Laboratory (PNNL) correlation generation rate predictions are bounded by the Epstein and Plys correlation generation rate predictions for all discharge areas where the Epstein and Plys correlation is applicable. An "if" statement is used to call the Epstein and Plys correlation for sampled discharge areas less than 12 mm^2. The Rosin-Rammler shape parameter for the Epstein and Plys correlation is also determined by area as:

$$q = \begin{cases} 2.30, & A \leq 4.45\ \text{mm}^2 \\ 3.47, & A > 4.45\ \text{mm}^2 \end{cases} \tag{AB-1}$$

Atmospheric Dispersion Choice by Accident Time. The STP uses RADIDOSE [26] and GXQ [27] to determine the atmospheric dispersion factor for various distances and release types. GXQ predicts atmospheric dispersion factors consistent with the guidance found in the Nuclear Regulatory Commission's Regulatory Guide (NUREG) 1.145 [28]. The atmospheric dispersion factors for 520 meters (i.e., the distance from the K West Basin Annex to the Columbia River) are listed in Table AB-3 for dispersion with and without considering plume meander effects. In this analysis, for accident durations less than one hour, plume meander is not considered. For accident durations greater than one hour, plume meander is applied. This is consistent with guidance in NUREG 1.145.

Table AB-3: Atmospheric dispersion factors [29]

Plume Meander	Atmospheric Dispersion Factor at 520 meters [s/m^3]
No	2.36E-3
Yes	5.66E-4

Appendix C
Discussion of Variable Input Parameter Ranges for the Probabilistic Calculation of an STP Spray Release Accident

Differential Pressure Across Breach. The differential pressure across the breach is conservatively assumed to be the same as the maximum pressure in the transfer lines, i.e., the discharge pressure of the booster pump in the K West Basin. A test report by CH2MHILL Plateau Remediation Company, PRC-STP-TR-00533 [30], presents performance testing measurements of a Watson-Marlow Bredel SPX80 industrial hose pump (i.e., peristaltic pump) used to boost the flow of slurry from the K West Basin to the Basin Annex. The pump was tested in two phases: 1) the pump was driven by a variable frequency drive (VFD) set at 1.5 times the motor current rating; and 2) the VFD was removed and the pump received maximum current. Both phases ran the pump to deadhead (i.e., zero flow) condition. The discharge pressure of the peristaltic pump is cyclical, but the pump flow rate remains constant. PRC-STP-TR-00533 presents the peak pressure and average pressure during each cycle for Phase 2 on page 42 of Attachment 1. The peak pressure at deadhead is 354 psi and the average pressure is 172 psi. The Xago HydroLance™ sludge retrieval tool requires a minimum flow rate of 70 gpm. The peak pressure at this flow rate was 244 psi and the average pressure was 136 psi. At the 80 gpm flow rate, the peak and average pressures were 107 psi and 40 psi, respectively. Additionally, the Engineered Container Retrieval and Transfer System (ECRTS) design has a safety-significant rupture disc that will vent slurry back into the basin at pressures greater than 115 psi.

Minimum pressure: 50 psig
Maximum pressure: 200 psig

Discharge Coefficient. Pacific Northwest National Laboratory (PNNL) [15] measured the discharge coefficient for water sprays with pressures of 100–380 psig and areas of 3.14–76 mm^2. Figure AC-1 shows a histogram for the discharge coefficient.

Minimum discharge coefficient: 0.50
Maximum discharge coefficient: 0.80

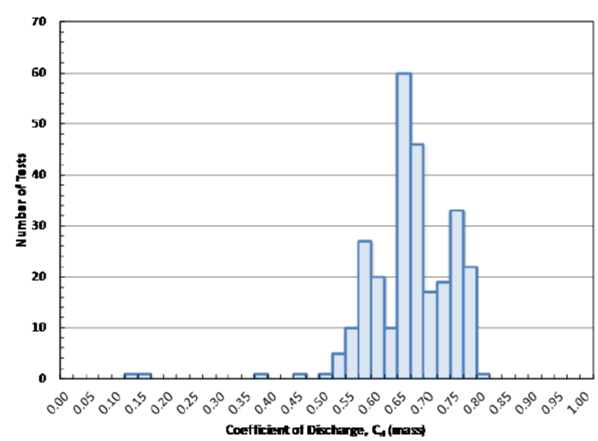

Figure AC-1: Discharge coefficient for water sprays from PNNL testing [15]

Discharge Area. The PNNL correlation [15] was developed using test measurements for discharge areas of 3.14–76 mm^2. The Epstein and Plys [12] correlation was developed using test measurements from 0.07–12 mm^2.

Minimum discharge area: 0.07 mm^2
Maximum discharge area: 76 mm^2

Sludge Volume. For an operational spray leak accident (i.e., non-seismically induced), the Sludge Treatment Project (STP) ECRTS preliminary documented safety analysis (PDSA) assumes that one egg crate of sludge and the sludge above that egg crate that slumps can be released [6]. The project team calculated an angle of repose of 40.6 degrees for the sludge in SCS-CON-230, but used a more conservative value of 35 degrees to calculate the maximum retrievable sludge volume of 1.11 m^3. The total volume of sludge in SCS-CON-230 is 3.5 m^3, of which 2.52 m^3 is located above the egg crates and 0.123 m^3 is located in one egg crate (there are eight egg crates per container) [29]. For a seismically induced spray release, the project team assumes that all the sludge above the egg crates plus one egg crate is retrievable. The retrievable sludge volume is assumed to be 2.64 m^3.

Minimum sludge volume: 1.11 m^3
Maximum sludge volume: 2.64 m^3

Sludge Solid Volume Fraction. Table 4-2 of HNF-SD-SNF-TI-015, Volume 2, lists the volume percent of water in the sludge in SCS-CON-230 [22]. These values can be used to determine the sludge solid volume fraction. The table provides two values; one is the "safety basis" value, the other is the "design basis" value. The design basis values are average values based on core sampling analysis. The safety basis values are based on statistical treatment of the data using a one-sided upper 95, 99 percent tolerance interval. The design basis sludge volume fraction is 0.27. The safety basis sludge volume fraction is 0.45.

Minimum sludge solid volume fraction: 0.27
Maximum sludge solid volume fraction 0.45

Sludge Density. Table 4-1 of HNF-SD-SNF-TI-015, Volume 2, lists the density of the sludge in SCS-CON-230 [22]. The design basis value is 2000 kg/m^3 and the safety basis value is 2800 kg/m^3.

Minimum sludge density: 2000 kg/m^3
Maximum sludge density: 2800 kg/m^3

Slurry (Mixture) Solid Volume Fraction. The STP ECRTS PDSA assumes the solid volume fraction of the transferred slurry is 0.075 [6]. The PDSA also states the Xago HydroLance™ sludge retrieval tool performed at an average of 0.044 solids volume fraction during testing. The project team anticipates the slurry solid volume fraction to be nominally less than 0.05. Page 9 of PRC-STP-CN-N-00874 [10] shows measured slurry volume fraction taken during testing of sand retrieval. The figure shows the solids volume fraction is sustained at approximately 0.11 for seven minutes. Given the uncertainty in the exact operation, the Board's staff team extended the value range.

Minimum slurry solid volume fraction: 0.040
Maximum slurry solid volume fraction: 0.15

Dose Conversion Factor of Sludge. The STP uses RADIDOSE [26] to calculate the total dose equivalent dose conversion factor for the sludge in SCS-CON-230. For public receptors, individual radionuclide dose conversion factors are based on International Commission on Radiological Protection (ICRP)-72. The ECRTS PDSA lists the dose conversion factor based on safety basis values of the sludge radionuclide inventories as 2.80E10 rem/m^3. Table 4-14e of HNF-SD-SNF-TI-015, Volume 2, lists design basis values for the radionuclide inventory of the sludge in SCS-CON-230. The Board's staff team used RADIDOSE to calculate the dose conversion factor using the design basis radionuclide inventory. The design basis dose conversion factor is 1.75E10 rem/m^3. The RADIDOSE outputs for the dose conversion factors using the design basis and safety basis radionuclide inventories are provided in Appendix D.

Minimum dose conversion factor of sludge: 1.75E10 rem/m^3
Maximum dose conversion factor of sludge: 2.65E10 rem/m^3

Sludge (Solids) Solid Volume Fraction in Evaporated Droplet at Receptor. The sludge solid volume fraction in the evaporated droplet at the receptor represents the percent of the droplet volume taken up by the solids. This input parameter only affects the spherical droplet evaporation model. Theoretically, this value could range from zero to one, representing a droplet with no solids, or a droplet that is only solids, respectively. Because the droplet density depends on the solid volume fraction in the droplet, the most conservative value is approximately 0.50. The Board's staff team chose a range that is wide, but still realistic.

Minimum sludge (solids) solid volume fraction in evaporated droplet at receptor: 0.05
Maximum sludge (solids) solid volume fraction in evaporated droplet at receptor: 0.95

Fraction of Liquid Remaining in Evaporated Droplet. The fraction of liquid remaining in the evaporated droplet represents the extent of evaporation of water in the droplet. This input parameter only affects the spherical droplet evaporation model. This value could theoretically range from zero to one, representing no evaporation of water, or fully evaporated (with air voids filling the volume not occupied by solids).

Minimum fraction of liquid remaining in evaporated droplet: 0.00
Maximum fraction of liquid remaining in evaporated droplet: 1.00

Droplet Dynamic Shape Factor. The droplet dynamic shape factor accounts for the increased drag force experienced by non-spherical droplets. Increased drag force reduces the gravitational settling velocity of the droplet and increases the equivalent droplet diameter compared to the aerodynamic droplet diameter. Table 6.2 of Crowe (recreated as Table AC-1 below) presents measured dynamic shape factors for various particle types [31].

In the atomization process, the liquid jet exiting an orifice breaks up due to aerodynamic forces acting at the interface between the jet and the quiescent air. Figure AC-2 shows photographs of the break up process. Atomization tends to form quasi-spherical liquid droplets. It is assumed that the solid particles in the slurry are contained in the liquid. As the droplet evaporates, the solid particles may form a quasi-spherical agglomerate structure. As seen in Table AC-1, dynamic shape factors can vary significantly depending on the structure of the droplet.

For its human respiratory tract model for radiological protection, ICRP recommends a dynamic shape factor of 1.5 [32]. This value is assumed in the absence of specific information about the physical characteristics of the aerosol.

In a review of the STP spray release methodology, a PNNL analyst used a dynamic shape factor 1.6 for use in a sensitivity study. The PNNL analyst also referenced shape factors for plate-shaped solid particles (κ=1.5) and needle-shaped particles (κ=1.7) [16]. Kotrappa et. al. measured PuO_2 aerosols from a glovebox and found dynamic shape factors of 1.8 [33].

Droplet agglomerates formed during the atomization process are not likely to form in a long, chain-like manner such as those found in combustion processes (i.e., dynamic shape factors will be less than 2.0).

Minimum droplet dynamic shape factor: 1.00
Maximum droplet dynamic shape factor: 2.00

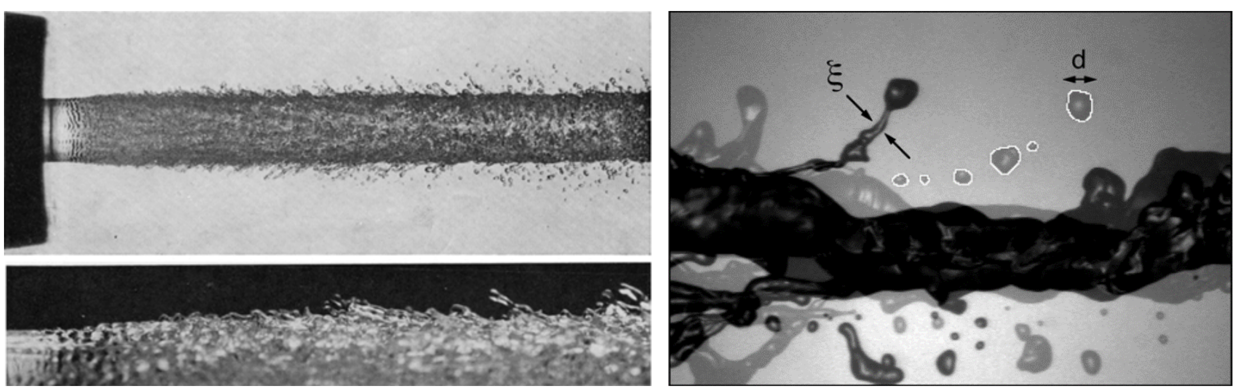

Figure AC-2: Photographs of fast water jets breaking up in air [34]

Table AC-1: Dynamic shape factors from Crowe [31]

Shape	Dynamic Shape Factor
Sphere	1.00
Cube	1.08
Cylinder (orientation averaged motion)	1.09 (for L/d=2)
	1.23 (for L/d=5)
	1.43 (for L/d=10)
Chain of spheres	1.12 (2-sphere chain)
	1.27 (3-sphere chain)
	1.32 (4-sphere chain)
Compact cluster of spheres	1.15 (3 spheres)
	1.17 (4 spheres)
Dust	
Bituminous coal	1.05-1.11
Quartz	1.36-1.82
Sand	1.57
UO_2	1.28
Talc (plate-like particle)	1.88
Agglomerates	
Carbonaceous smoke	3.26-6.77
Pb fume	1.5-3.5
$(PuU)O_2$	1.96-2.85

Appendix D
RADIDOSE Outputs for Dose Conversion Factors

Design Basis Radionuclide Inventories

Dose Results for the Postulated Accident:				
User-defined mixture ("InSource" page)				
		T-Plant / K-Basin Sludge		
Ground Level Near A Building (Wake Effects)				**100 Area**
Total Respirable Release:		1.00E+00	Liter	
Dose Factors:	ICRP 68, 5μm	ICRP 72 for Adult		Release
	Collocated	**Onsite**	**Offsite**	Duration
Receptor:	**Worker**	**Public**	**Public**	0.5 h
Distance:	100 m	520 m	10,100 m	
X/Q:	2.03E-02	2.36E-03	4.58E-05	s/m3
Breathing Rate:	3.35E-04	3.29E-04	3.29E-04	m3/s
Unit DCF:	1.85E+07	1.75E+07	1.75E+07	rem/Liter
Total Dose:	**1.26E+02**	**1.35E+01**	**2.63E-01**	**rem**
Consequence:	High	na	Low	

Material source amounts are listed on the "UnitDF" page.

Safety Basis Radionuclide Inventories

Dose Results for the Postulated Accident:				
User-defined mixture ("InSource" page)				
		T-Plant / K-Basin Sludge		
Ground Level Near A Building (Wake Effects)				**100 Area**
Total Respirable Release:		1.00E+00	Liter	
Dose Factors:	ICRP 68, 5μm	ICRP 72 for Adult		Release
	Collocated	**Onsite**	**Offsite**	Duration
Receptor:	**Worker**	**Public**	**Public**	0.5 h
Distance:	100 m	520 m	10,100 m	
X/Q:	2.03E-02	2.36E-03	4.58E-05	s/m3
Breathing Rate:	3.35E-04	3.29E-04	3.29E-04	m3/s
Unit DCF:	2.80E+07	2.65E+07	2.65E+07	rem/Liter
Total Dose:	**1.91E+02**	**2.05E+01**	**3.99E-01**	**rem**
Consequence:	High	na	Low	

Material source amounts ar listed on the "UnitDF" page.

SCS-CON-230 Radionuclide Inventories

	Design Basis Ci/m^3	Safety Basis Ci/m^3	Design Basis Ci/L	Safety Basis Ci/L
Am-241	1.34E+02	2.05E+02	1.34E-01	2.05E-01
Np-237	1.26E-02	2.12E-02	1.26E-05	2.12E-05
Pu-238	1.76E+01	2.70E+01	1.76E-02	2.70E-02
Pu-239	8.08E+01	1.13E+02	8.08E-02	1.13E-01
Pu-240	4.73E+01	6.74E+01	4.73E-02	6.74E-02
Pu-241	1.02E+03	1.84E+03	1.02E+00	1.84E+00
Pu-242	2.14E-02	3.82E-02	2.14E-05	3.82E-05
Co-60	3.84E-01	6.60E-01	3.84E-04	6.60E-04
Cs-134	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Cs-137	6.36E+02	4.06E+03	6.36E-01	4.06E+00
Ba-137m	6.01E+02	3.83E+03	6.01E-01	3.83E+00
Eu-154	4.08E+00	5.98E+00	4.08E-03	5.98E-03
Eu-155	5.21E-01	8.86E-01	5.21E-04	8.86E-04
Sr-90	1.09E+03	1.99E+03	1.09E+00	1.99E+00
Y-90	1.09E+03	1.99E+03	1.09E+00	1.99E+00
Tc-99	0.00E+00	0.00E+00	0.00E+00	0.00E+00
U-234	2.16E-01	3.89E-01	2.16E-04	3.89E-04
U-235	9.39E-03	1.29E-02	9.39E-06	1.29E-05
U-236	2.95E-02	4.43E-02	2.95E-05	4.43E-05
U-238	2.03E-01	2.81E-01	2.03E-04	2.81E-04

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